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Key Points:

- We investigated the equatorial diameter of “quiet” solar corona at low radio frequencies during the descending phase of Sunspot Cycle 24
- Localized sources of emission in the radio images were identified and removed using iterative multi-Gaussian curve fitting technique
- The minimum radius of the “quiet” solar corona at a typical frequency like 53 MHz was found to be $\approx 1.16 R_{\odot}$

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Low-Frequency Radio Observations of the “Quiet” Corona During the Descending Phase of Sunspot Cycle 24

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Abstract We carried out a statistical study of the “quiet” solar corona during the descending phase of the Sunspot Cycle 24 (i.e., January 2015 to May 2019) using data obtained with the Gauribidanur RAdioheliograph (GRAPH) at 53 and 80 MHz simultaneously. Our results show that the equatorial (east-west) diameters of the solar corona at the above two frequencies shrunk steadily. The decrease was found to be due to a gradual reduction in the coronal electron density (N_e). Independent estimates of N_e in the equatorial region of the “background” corona using white-light coronagraph observations indicate a decline consistent with our findings.

1. Introduction

One of the well-established results from the white-light observations during total solar eclipses and with coronagraphs is that the shape/size and electron density of the corona varies with the sunspot cycle. This is because of the close correspondence between the coronal brightness and the electron density, which in turn is an indicator of the coronal magnetic field (see, e.g., MacQueen et al., 2001). These studies were primarily about the “global” corona, which included structures like the coronal streamers also. We wanted to investigate the “quiet” solar corona (i.e., the corona distinct from emission due to transient and long-lasting discrete sources) at radio frequencies during the Sunspot Cycle 24 since it could provide independent results related to the latter. Observations of thermal bremsstrahlung radio emission from the “quiet” solar corona at frequencies <100 MHz are expected to be particularly useful in this connection since the radiation originates fully in the corona. The corona above the visible solar disk and off the solar limb can be simultaneously imaged, hence the present work.

2. Observations

The radio observations were carried out using the facilities operated by the Indian Institute of Astrophysics (IIA) in the Gauribidanur observatory (Ramesh, 2011, 2014; <https://www.iiap.res.in/?q=centers/radio>). Two-dimensional radio images obtained with the *Gauribidanur RAdioheliograph* (GRAPH; Ramesh et al., 1998, 1999b, 2006) at 80 and 53 MHz during the period January 2015 to May 2019 were used. The GRAPH is a T-shaped long radio interferometer array, and it has an angular resolution (“beam”) of $\approx 4' \times 6'$ (R.A. \times decl.) and $\approx 6' \times 9'$ at the above two frequencies, respectively. The integration time is ≈ 250 ms, and the observing bandwidth is ≈ 2 MHz. Observations are carried out every day for ≈ 2.5 hr on either side of the transit of the Sun over the local meridian in Gauribidanur. However, for the present work, we limited ourselves to the data obtained for a period of ± 15 min around the transit. Since the source zenith angle will be the least during that time, any possible refraction effects due to the ionosphere are generally minimal (Jacobson et al., 1991; Mercier, 1996; Stewart & McLean, 1982). Note that the local latitude of Gauribidanur is $\approx +14^\circ$ N. This is within the decl. range of -23° S to $+23^\circ$ N over which the Sun moves back and forth every year. So, even when the Sun is at -23° decl., its elevation for GRAPH would be high ($\approx 53^\circ$). For radio spectral data, we used observations with the *Gauribidanur LOW-frequency Solar Spectrograph* (GLOSS; Ebenezer et al., 2001, 2007; Hariharan et al., 2016; Kishore et al., 2014), *Gauribidanur Radio Spectro-Polarimeter* (GRASP; Hariharan et al., 2015; Kishore et al., 2015; Sasikumar Raja et al., 2013), and *e-CALLISTO* (Benz et al., 2009; Monstein et al., 2007). We also used data obtained with the *Gauribidanur Radio Interferometric Polarimeter* (GRIP; Ramesh et al., 2008). The combined use of the aforementioned imaging, spectral, and polarimetric data helps to understand the radio signatures associated with the corresponding solar activity

in a better manner (see, e.g., Sasikumar Raja & Ramesh, 2013). The optical data were obtained in white-light with the COR1 coronagraph of the *Sun-Earth Connection Coronal and Heliospheric Investigation* (SECCHI; Howard et al., 2008) on board the *Solar Terrestrial Relationship Observatory-A* (STEREO-A, <https://cor1.gsfc.nasa.gov/>).

The GRAPH data were carefully selected such that (i) no $H\alpha$ and/or X-ray flares, coronal mass ejections (CMEs), and short-/long-duration nonthermal radio burst activities were reported during our observing period as well as for ≈ 30 min before and after (<ftp://ftp.swpc.noaa.gov/pub/warehouse>; <http://sidc.oma.be/cactus/>). In addition to the above, we verified the presence/absence of radio burst activities using data obtained with GLOSS, GRASP, and e-CALLISTO also. Observations with the GRIP were particularly useful to verify the presence/absence of discrete sources of weak nonthermal emission like noise storm continuum on any given day via their circularly polarized radio emission and accordingly select the GRAPH data (see, e.g., McCauley et al., 2019; Mugundhan et al., 2018; Ramesh et al., 2011). Note that observations with a correlation radio interferometer with mutually perpendicular linearly polarized antennas as in GRIP are sensitive for circular polarization measurements (see, e.g., Thompson et al., 2001). With all the aforementioned checks, we unambiguously identified GRAPH observations of “quiet” Sun for 494 days; (ii) the spectral index between 53 and 80 MHz is expected to be in the range $\approx +1.6$ to $+3.9$ for thermal emission from the solar corona (Erickson et al., 1977; Oberoi et al., 2017; Ramesh et al., 2000, 2006; Subramanian & Sastry, 1988). But we considered only observations with spectral index $+2.0 \pm 0.2$ from the aforementioned 494 days of observations to minimize confusion due to possible contribution of nonthermal emission and/or temperature gradients in the corona (see, e.g., Subramanian & Sastry, 1988). This resulted in 382 days of concurrent data at the two frequencies for further analysis.

3. The Method

We wanted to investigate the size of the “quiet” solar corona by measuring its equatorial diameter at different epochs using two-dimensional (2-D) radio imaging data obtained with the GRAPH. Note that we limited ourselves to diameter measurements since it is a directly observable quantity. The equatorial diameter was particularly chosen for the study due to the comparatively better and declination independent angular resolution of the GRAPH in the east-west direction. Further, the polar diameter are generally biased by the equatorward extension of the polar coronal holes during the descending phase of a sunspot cycle (Hundhausen et al., 1981). To obtain the equatorial diameter, we determined the one-dimensional (1-D) brightness distribution averaged over an angular width of $\approx 5'$ centered on the solar equator (i.e., where the decl. coordinate in the y axis is equal to the decl. of the Sun on that day) in the 2-D images obtained with the GRAPH (see, e.g., Figure 1). Since the above angular width is small, the “critical” plasma level (corresponding to any particular observing frequency) at different locations within the enclosed coronal regions can be assumed to be at the same heliocentric distance. Each 1-D brightness distribution obtained as mentioned above was reproduced using an iterative multi-Gaussian least squares curve fitting technique as described in Ramesh et al. (2006). The minimum width of each Gaussian profile was limited to $1'$, the smallest source size reported at frequencies < 100 MHz (Kathiravan et al., 2011; Mugundhan et al., 2016, 2018; Ramesh & Ebenezer, 2001; Ramesh & Sastry, 2000; Ramesh et al., 1999a, 2012). The typical discrete thermal sources in the above frequency range are mostly the radio counterparts of large-scale structures like the coronal streamers and/or coronal holes. The source sizes are $\approx 8'$ at 73.8 MHz (Kundu et al., 1977; Lantos et al., 1987; Schmahl et al., 1994). The above size measurements indicate that the angular resolutions of the GRAPH at 53 and 80 MHz are reasonably sufficient to identify discrete sources of thermal radio emission at the respective frequencies in the present case. This is true even for weak noise storm continuum sources, the other suspected candidate of slowly varying emission at frequencies < 100 MHz (Lantos, 1999), since their angular size is $\approx 10'$ at 73.8 MHz (Kundu & Gopalswamy, 1990).

We also imposed the following conditions to consider the data obtained at a particular epoch for further analysis: (i) The fits for the 53 and 80 MHz observations must have one Gaussian profile each with width $> 32'$ and the width of such a profile in the fit for the 53 MHz observations should be larger than the corresponding 80 MHz profile on the same day; (ii) the discrete solar radio sources identified from the fit should be present at both the frequencies; and (iii) the sum of the amplitudes of the Gaussian profiles used to fit the observed 1-D brightness distribution at any given position on the latter should be nearly equal to the observed amplitude there. These conditions further reduced our data set to 336 days (see section 2). The iterative fit procedure was carried out till the difference in the amplitudes between the fit and the observations

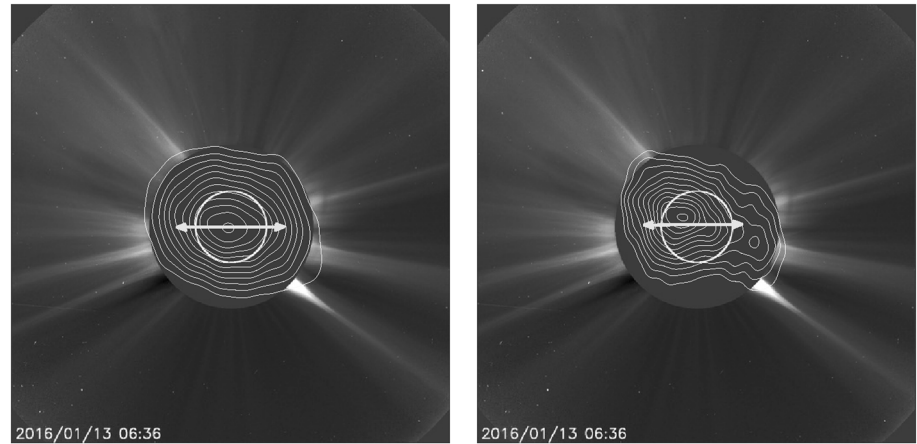


Figure 1. GRAPH images of the solar corona obtained on 13 January 2016 at 53 and 80 MHz superposed on the SOHO/LASCO-C2 white-light image obtained on the same day around the same time. Solar north is straight up, and east is to the left. The “white” color open circles represent the size of the solar photosphere. The concentric, filled “black” color circles indicate the occulting disk of the coronagraph. Its radius is $\approx 2.2 R_{\odot}$. The horizontal “white” color lines indicate the equatorial diameter of the “quiet” solar corona at the respective frequencies estimated using the method described in section 3 of the text (see Figure 2).

is ≈ 0.05 SFU ($1 \text{ SFU} = 10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$), the minimum detectable flux density with GRAPH. In addition to the Gaussian of width $> 32'$, we used a maximum of four additional Gaussians to get the best fit on any given day at each of the two frequencies.

The Gaussian profiles that satisfied the criteria (i) mentioned above were considered to represent the “background” corona, and their actual widths in the respective fits were considered to be the equatorial diameters at the corresponding frequencies for the observations on a particular day. Assuming Gaussian shape for the GRAPH beam, we eliminated its contribution to the diameter estimate using the formula $\theta_s = \sqrt{(\theta_e^2 - \theta_b^2)}$, where θ_s is the source size without beam contribution, θ_e is the estimated source size as described above, and θ_b is the beam size. An example of the diameter measurements using the above method is shown in Figure 2. There is excellent correspondence between the observations and the multi-Gaussian fit. Discrete sources close to the limb that are not so clearly discernible in the 2-D radio images (e.g., the source near the

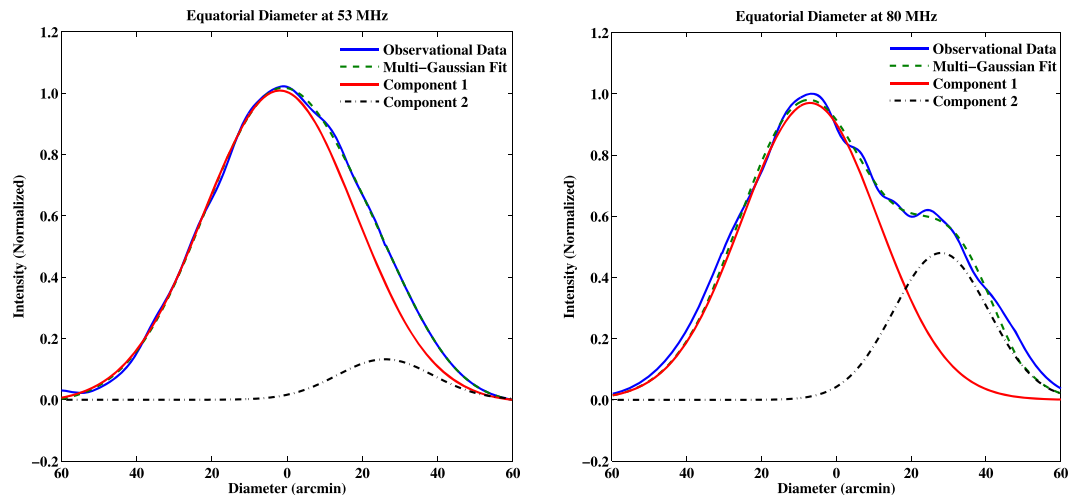


Figure 2. One-dimensional equatorial brightness distribution obtained from the GRAPH radioheliograms at 53 and 80 MHz (see Figure 1) based on the methodology described in section 3. Two Gaussian profiles, red color (solid line) and black color (with dash-dotted symbols), were used to match the observations (blue color profile). The green color profile (with dash symbols) is the sum of the aforementioned two Gaussian profiles used for the fit. The Chi-square fit errors are $< 1\%$ at both 53 and 80 MHz.

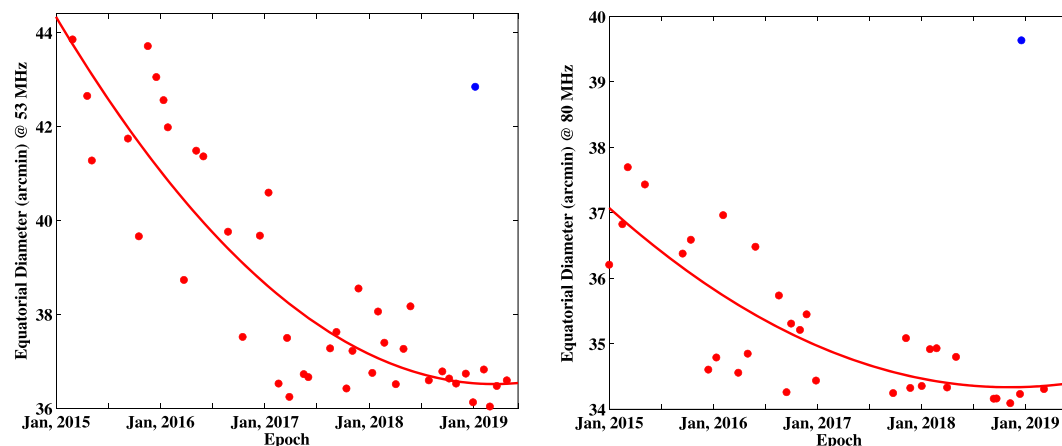


Figure 3. The data points in red color are the monthly minimum values in the equatorial diameters of the solar corona at 53 MHz (left panel) and 80 MHz (right panel) during the period January 2015 to May 2019. The solid lines in red color are the quadratic least squares fit to the data points. The isolated blue color data point indicates the monthly maximum value in the equatorial diameter during 2019 January. It is significantly larger than the corresponding monthly minimum value even during the minimum period of Sunspot Cycle 24 like the aforementioned epoch.

west limb in the 80 MHz image in Figure 1 is less prominent in the 53 MHz image) are also effectively identified and removed (see Figure 2). The incomplete removal of such sources could lead to a larger equatorial diameter.

A comparison of the radio and white-light images in Figure 1 indicate that the radio contours are elongated in the east-west direction. This is predominantly due to enhanced radio emission associated with the multiple, closely spaced bright white-light structures seen above the occulting disk of the coronagraph in the east and west directions. The contours appear smoothed because of the differences in angular resolution between radio and optical observations. An inspection of the near-Sun ($\approx 1.05\text{--}3 R_{\odot}$) white-light coronagraph images (https://download.hao.ucar.edu/2016/01/12/20160113_020824_kcor_l1_cropped.gif) is in support of the above arguments. Note that SOHO/LASCO-C2 observations correspond to heliocentric distances $>2.2 R_{\odot}$, and hence, the structures are seen distinctly. The differences between the 53 and 80 MHz images themselves are chiefly due to the comparatively higher angular resolution of the GRAPH at 80 MHz and scattering of radio waves by density inhomogeneities in the solar corona (Aubier et al., 1971; Ramesh, 2000; Thejappa & Kundu, 1992). It was shown by Thejappa and MacDowall (2008) that positional displacements due to scattering could be $\sim 5'$ at 50 MHz compared to 73.8 MHz. Earlier, Sastry (1994) had reported observations of $\sim 10'$ shift between the centroids of the “quiet” Sun and the optical Sun. The “resolved” discrete radio source near the west limb in the 80 MHz image as against the 53 MHz image, and the separation between the centroids of the “quiet” Sun in the 53 and 80 MHz images is consistent with the above arguments.

Figure 3 shows the monthly minimum values in the equatorial diameters of the solar corona at 53 and 80 MHz during the period January 2015 to May 2019 estimated using the above methodology. The gap in the data points during 2017, particularly at 80 MHz, is due to the use of GRAPH for observations of background cosmic radio sources that are occulted by the solar corona at the above frequency (see, e.g., Ramesh et al., 2001; Sasikumar Raja et al., 2016; Slee, 1961). We chose the monthly minimum values of the diameters since they are more likely to represent the “quiet” solar corona, which at low radio frequencies is supposed to be the corona that is nearly free of localized thermal and/or nonthermal sources (see, e.g., Leblanc & Le Squeren, 1969).

4. Analysis and Results

An inspection of Figure 3 and the quadratic least squares fits to the data points there reveals a gradual decrease in the equatorial diameters at both 53 and 80 MHz from January 2015. There is a high degree of correlation ($\approx 74\%$) between the diameter values at the above two frequencies (Figure 4). This indicates that the discrete sources have been uniformly identified and removed at both 53 and 80 MHz. Note that if the diameters had been over estimated due to possible incomplete removal of the discrete sources, particularly near the limb(s), then the distribution of the monthly minimum diameter values at 53 and 80 MHz could

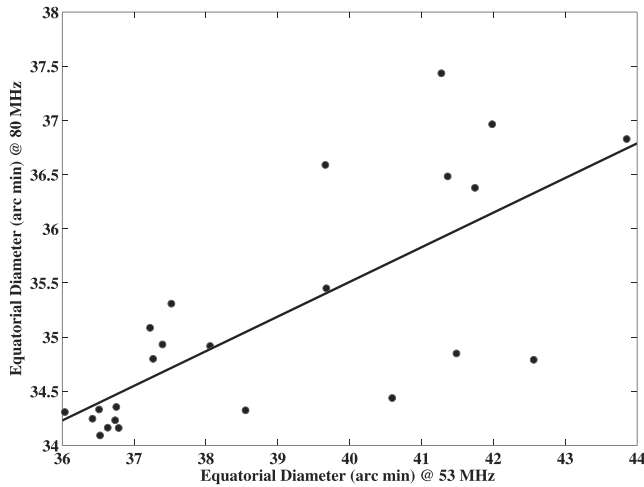


Figure 4. Correlation between the 53 and 80 MHz diameters in Figure 3. The correlation coefficient is 74%. The “black” line is the linear least squares fit to the data points.

of the “quiet” Sun, we find that $N_e \approx 3.5 \times 10^7 \text{ cm}^{-3}$ appears to the lowest value ever reported at $r \approx 1.16 R_\odot$ (see, e.g., Figure 2 in Warmuth & Mann, 2005). This implies that radio emission at 53 MHz from the “quiet” Sun originated at $r \approx 1.16 R_\odot$ during the minimum phase of Sunspot Cycle 24. Note that the average height of the coronal type II radio bursts during the declining phase of Sunspot Cycle 23 was found to be smaller compared to their average height during the maximum phase due to a similar decrease in N_e (Gopalswamy et al., 2009).

We verified the aforementioned decrease in N_e during the descending phase of Sunspot Cycle 24 by independently estimating N_e at $r \approx 1.55 R_\odot$ in the equatorial region of the “quiet” corona using the linearly polarized brightness (pB) measurements with STEREO-A/COR1 (<http://sd-www.jhuapl.edu/secchi/lz/L0/a/seq/>) and the inversion technique based on spherically symmetric polynomial approximation (SSPA; Wang & Davila, 2014; Wang et al., 2017; solar.physics.montana.edu/wangtj/sspa.tar). The N_e estimates were obtained at $r \approx 1.55 R_\odot$ since it is the nearest distance to/above the STEREO-A/COR1 occulting disk (radius $\approx 1.4 R_\odot$), which is close to the equatorial diameters indicated by the overall fits in Figure 3. A set of three STEREO-A/COR1 images taken sequentially around $\approx 06:30$ UT with the linear polarizer at angles 0° , 120° , and 240° with respect to the reference direction were used to construct the pB image. The time interval

between the image obtained at each of the aforementioned positions of the polarizer is ≈ 9 s. Note that STEREO-A/COR1 pB images obtained at a different time on the same day could have also been used since our interest is mainly in the “quiet” corona whose characteristics like N_e generally vary on comparatively longer time scales only. Note that there were no data available from STEREO spacecraft for January 2015 to December 2015 as it passed behind the Sun. So we used January 2016 to May 2019 data. We analyzed data obtained on three different days each month, with an interval of 10 days, during the above period. The images were processed to align with the solar north and calibrated to remove the instrumental scattered light. The background was subtracted using data derived from a complete solar rotation. We used SSPA to obtain 2-D maps of N_e along the equator, that is, at position angles (PA) $\approx 90^\circ$ and $\approx 270^\circ$. We averaged the N_e from PA $\approx 90^\circ \pm 15^\circ$ and $\approx 270^\circ \pm 15^\circ$ at $r \approx 1.55 R_\odot$ to reduce the variation in N_e .

Figure 5 shows the N_e values thus obtained on 117 different days during interval January 2016 to May 2019 when there were no coronal streamers and/or coronal holes in the above PA range. The scatter in the N_e estimates are mostly due to the assumption of spherically symmetric approximation for the inversion and the errors associated with

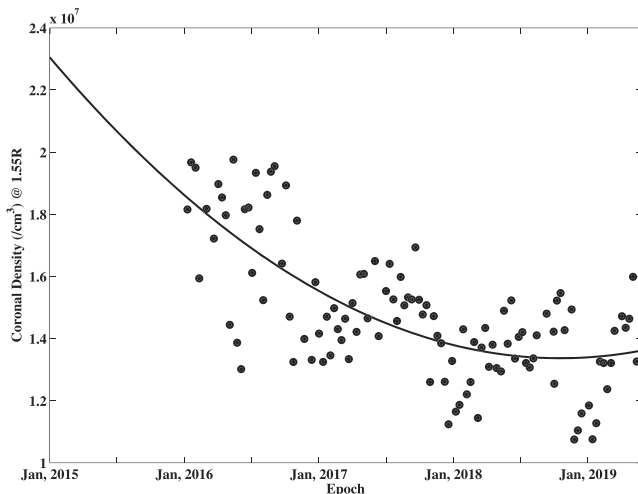


Figure 5. Estimates of N_e at $r \approx 1.55 R_\odot$ from white-light (STEREO-A/COR1) observations during the period January 2016 to May 2019. The “black” line is the quadratic least squares fit to the data points.

instrumental background subtraction due to bad pixels in the detector. The quadratic least squares fit to the data points in Figure 5 indicates a decreasing trend in N_e . The maximum and minimum values of N_e obtained from the fit are $\approx 2.3 \times 10^7 \text{ cm}^{-3}$ (January 2015) and $\approx 1.3 \times 10^7 \text{ cm}^{-3}$ (January 2019), respectively. This implies that N_e had decreased by a factor of ≈ 1.8 at $r \approx 1.55 R_\odot$ in the above interval during the descending phase of Sunspot Cycle 24. This is reasonably consistent with the ≈ 2.3 times decrease in N_e estimated from the GRAPH observations at $r \approx 1.16 R_\odot$ (see Figure 3). The nearly equal factor by which N_e has decreased at two different heliocentric distances suggest an overall decline in N_e .

5. Summary

We investigated the changes in the size of the solar corona during the period January 2015 to May 2019 (descending phase of Sunspot Cycle 24) using data obtained with the GRAPH at 53 and 80 MHz. Our results indicate that the heliocentric distances at which radio emission at the above two frequencies originate in the equatorial region of the “quiet” solar corona gradually decreased during the said period due to a decrease in N_e . We independently verified the latter using white-light coronagraph estimates of N_e in the equatorial region of “background” corona that was devoid of coronal streamers and/or coronal holes.

Data Availability Statement

Data used in the study are available online (at <https://www.iap.res.in/gauribidanur/home.html>).

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